Engine Controls for Emergency Aircraft Operation

Propulsion Controls and Diagnostics Workshop

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Acknowledgments

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  - ***FastER Project Manager -*** Jonathan Litt
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  - U Conn
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Agenda

- Motivation
- Control Law Development
  - Actuation Options
  - Emergency Control Modes
  - Control Architectures
- Results
  - Actuation Effectiveness Study
  - Fast Response Modes
  - Emergency Scenario 2 Study
- Summary

Motivation

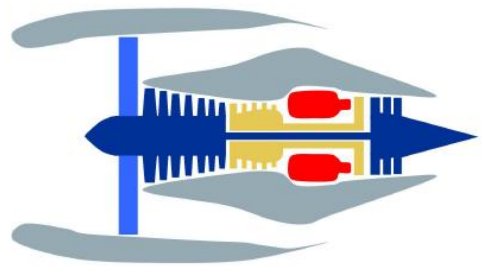
Aviation Safety Program *Integrated Resilient Aircraft Control*

Why Off Nominal Operation?

Loss of Control

United Flight 232 in Sioux City, IA
July 1989

American Flight 587 in Queens, NY
November 2001



What Can The Engines Do To Help?

Air Transat 961 from
Varadero, Cuba March 2005

Runway Incursion

USAir 1493 / SkyWest 5569 at LAX
February 1991

Comair Flight 5191 in Lexington, KY
August 2007

Project Goal and Objectives

Fast-response Engine Research (FastER)

"Arrive at a set of validated multidisciplinary integrated engine control design tools and techniques for enabling safe flight in the presence of adverse aircraft conditions…"

- Improve Flight *Safety* and *Survivability* of Aircraft Under Abnormal or Emergency Conditions Such As Faults, Damage or Upsets
- Investigate and Design a Notional Fast-response Engine Controller:
  - Boost (Or Recover) Engine Capability by Relaxing Normal Physical and Operational Limits During an Emergency Until Aircraft Lands Safely
  - Enhanced Engine Capability Is Primarily *Increased and Faster Thrust*; Produced By Balancing Against Operating Margins and Remaining Life Of Critical Engine Components

Engine Challenges:
- Response Typically Slow as Compared to Aircraft Control Surfaces
- Thrust Levels Typically Limited to Meet Full-Life Specs

Ground Rules

Leading to Fast-response Engine Controller Design

Target Application:

- Generic High-Bypass Turbofan Engine
- Generic Commercial Transport Aircraft

For Research:

- Select and Focus On Two Specific Representative Scenarios
- Study Impact of Over-Thrust Operation on Engine Component Life
- Evaluate Impact of Fast Response on Engine Transient Stability
- Determine Means of Selectively Extending Engine Operation Limits
- Research Use of Traditional and Unconventional Control Modes
- Facilitate Development of New Strategies/Concepts By Other Researchers

Assume:

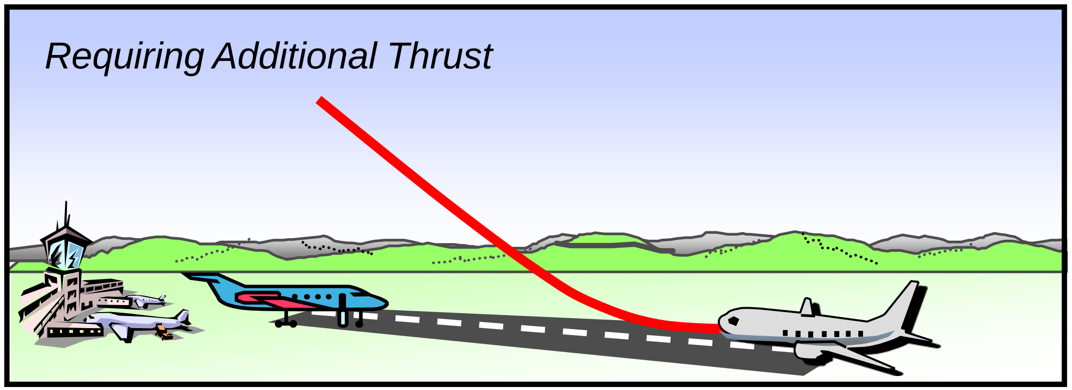
- No Damage to the Engine, But Do Consider Normal Degradation
- *Adverse Condition Indicator* Provided to Engine Controller
- Aircraft Scenarios Start from a Stabilized Condition – Don’t Worry About Recovery

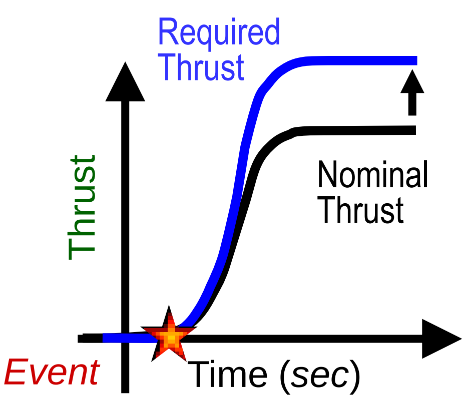
Develop and Demonstrate a *Notional* Controller That Provides Increased and Faster Thrust During Emergency Operations

Requirements Definition

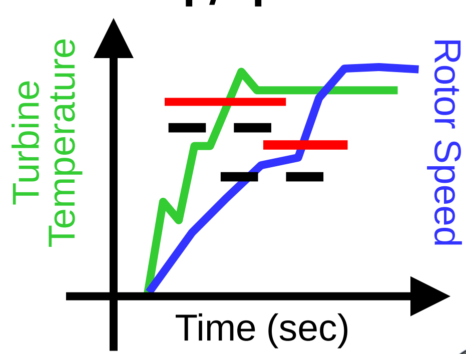
Aviation Safety Program | *Integrated Resilient Aircraft Control*

Scenario ❶ Takeoff Runway Incursion





Max Temp/Speed Limits



Adverse Condition

Plane Crossing Runway During Takeoff Roll

Operating Conditions

Flight Conditions: 250 feet / 100 kts

Throttle Setting: Full Power

Pilot Action

Snap Full Throttle – Hard Pull Up

Derived Engine Requirements

- Increased Maximum Thrust
- Short Duration (< Minute)
- Ensure Engine Does Not Fail

Scenario

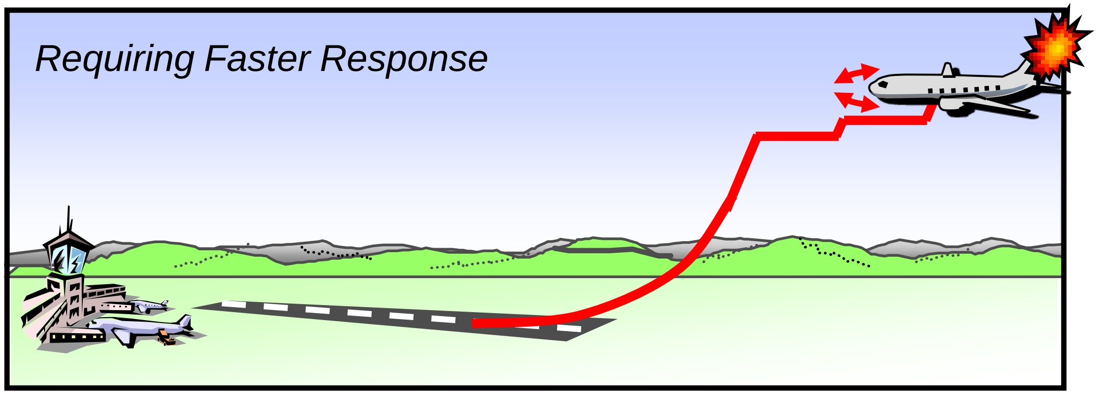
Durability Analysis for Increased Thrust

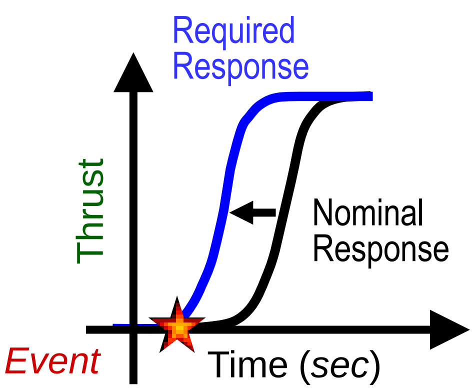
Real-Time Trading of Part Life for Thrust

Requirements Definition

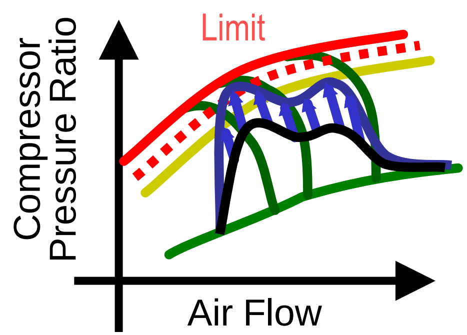
Aviation Safety Program ***Integrated Resilient Aircraft Control***

Scenario ❷ Loss of Control – Rudder / Tail Failure





Stall / Surge Margins



Adverse Condition

Sudden Loss of Rudder Control

Operating Conditions

Flight Conditions: 4500 feet / M=0.25

Throttle Setting: 6500 lbf Thrust

Start from Stabilized Condition

Pilot Action

Asymmetric Engine Thrust Modulation

Derived Engine Requirements

- Decrease Accel / Decel Times
- Maintain Adequate Margins / No Stall

Requirements

Base Engine (τ) **→ ζ = 0.2**

Fast Engine **(0.5 τ) → ζ = 0.3**

Faster Engine **(0.25 τ) → ζ = 0.4**

Scenario

Operability Analysis for Fast Response

Real-Time Stability Audit

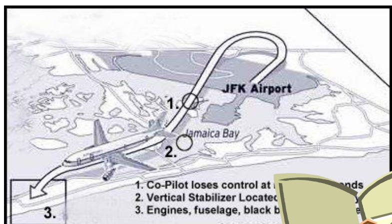
Three Phase Program Structure

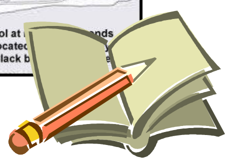
Aviation Safety Program | **Integrated Resilient Aircraft Control**

Working in a Simulation Environment

Requirements

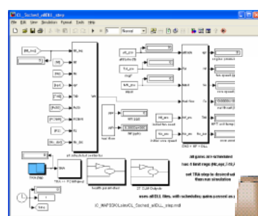
- **Scenario Simulations**
- **Requirements Definition**





Control Law Development

- **Theories & Methods**
- **Available Engine Capabilities**
- **Simulation Evaluations**
- **Risk Trade-offs**

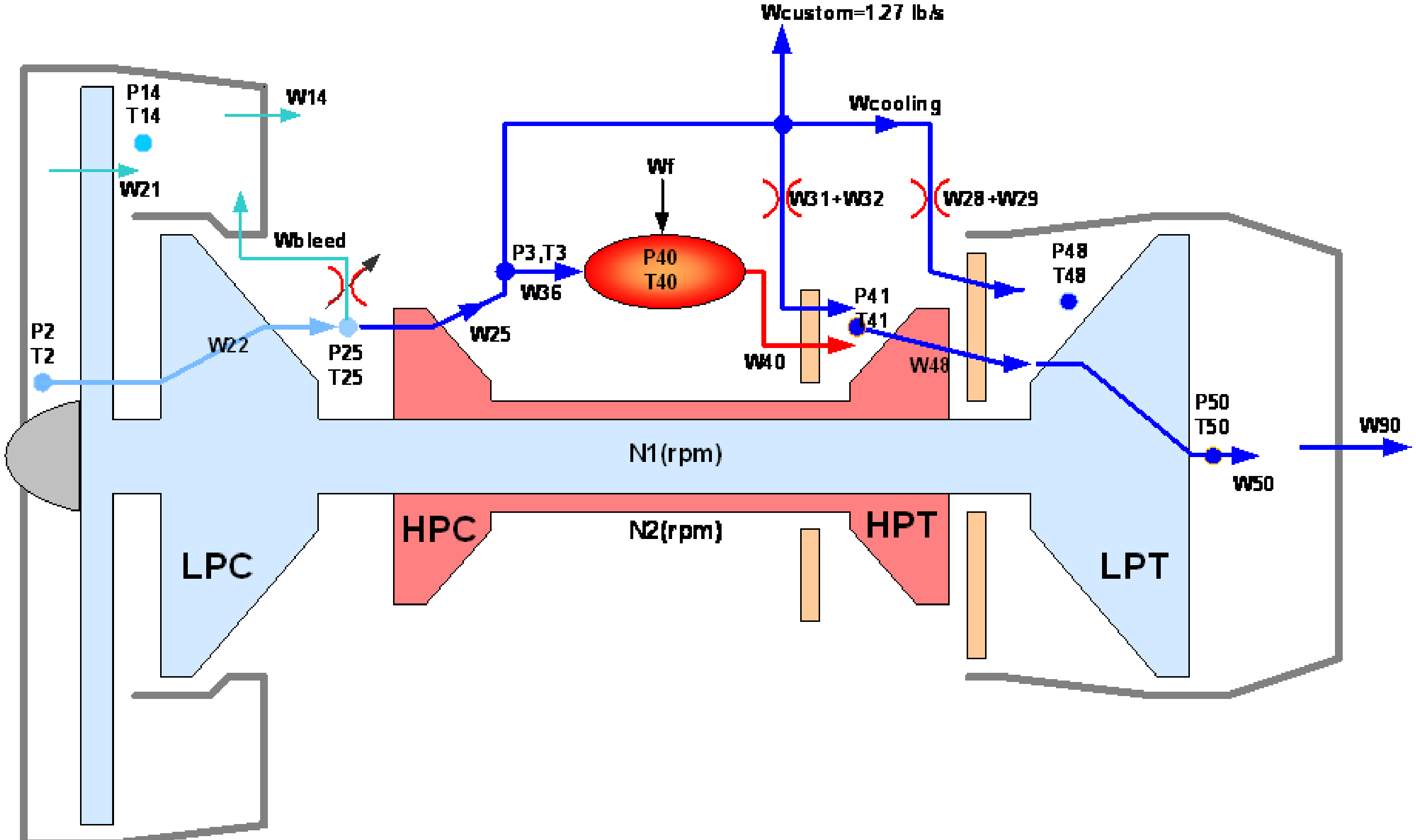


Demonstration of Capability

- **Integ. of Engine and A/C Models**
- **Integ. of Engine and A/C Controls**
- **Simulation Evaluations**

C-MAPSS40k* Engine

Aviation Safety Program — *Integrated Resilient Aircraft Control*



Twin-Spool Engine Schematic

Technical Challenges

- **Establish the Baseline Engine Control System**
- **Flow down the aircraft, engine and control requirements**
- **Identify Engine Control System Actuation Options**
  - **Consider Both Existing and New Actuation Approaches**
  - **Rank Actuation Options Based on Effectiveness and Impact**
- **Develop Engine Control Modes for Emergency Maneuvers**
  - **Down select to Three High Potential Modes**
- **Design Control Laws for High Potential Emergency Control Modes**
  - **Use Both Classical and Modern Design Methods**
  - **Take Into Account Time/Event-Varying Constraints**
  - **Incorporate Risk Evaluation in Design**
- **Evaluate Designs Through Simulation**
  - **Evaluate rapid acceleration and fan bleed modes**
  - **Incorporate fan bleed in C-MAPSS40k – (Incorporated in C-MAPSS40k* Simulation)**
  - **Integrate C-MAPSS40k with the aircraft General Transport Model (GTM) – (C-MAPSS40k* integrated with scaled GTM)**
  - **Incorporate differential thrust - yaw control in GTM**
  - **Evaluate differential thrust control mode**
- **Develop control design methods that trade performance and risk metrics, while maintaining engine safety limits**

Potential Actuation Options
Compressor Example

	Existing Commercial Engine Actuation	Higher Resp Actuation (in Existing Package)	New or Advanced Actuation
Compressor	CGV, RCVV, BV, ACC	CGV, RCVV, ABV, ACC	ACC, ASC, Aspirated Tip, water injector, gas injector

Acronym	Definition
ACC	active clearance control
ABV	active bleed valve
ASC	active stall/surge control
BV	bleed valve
CGV	compressor guide vane
RCVV	rear compressor variable vane

Can our objectives be achieved without substantial, new actuator development?

Control Law Development

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Potential Emergency Engine Control Modes

Emergency Control Mode	Thrust Objective	Technology Challenge	Operability Issue	
Stall Margin Feedback	Response	Reliable Stall Margin Estimation	Compressor Stall/Surge	*
Variable Thrust Reverser	Response, Increased Delta	Reliable, low weight actuation	Weight, Complexity	
Reduced Temperature Margin	Maximum	Improved turbine engine life estimation	Blade Melt, Disk Failure	*
High Speed Flight Idle	Response	Thrust "dumping"	Localized Overheating	*
Rotor Torque Augmentation	Response	Actuator and power source for additional engine rotor torque	Weight, Complexity	
Improved BOM Modes	Response, Maximum	Higher Response versions of existing actuation	Heavier Actuation	*
Risk Assessment	High	Medium	Low	

Fast Response Engine Control Architecture

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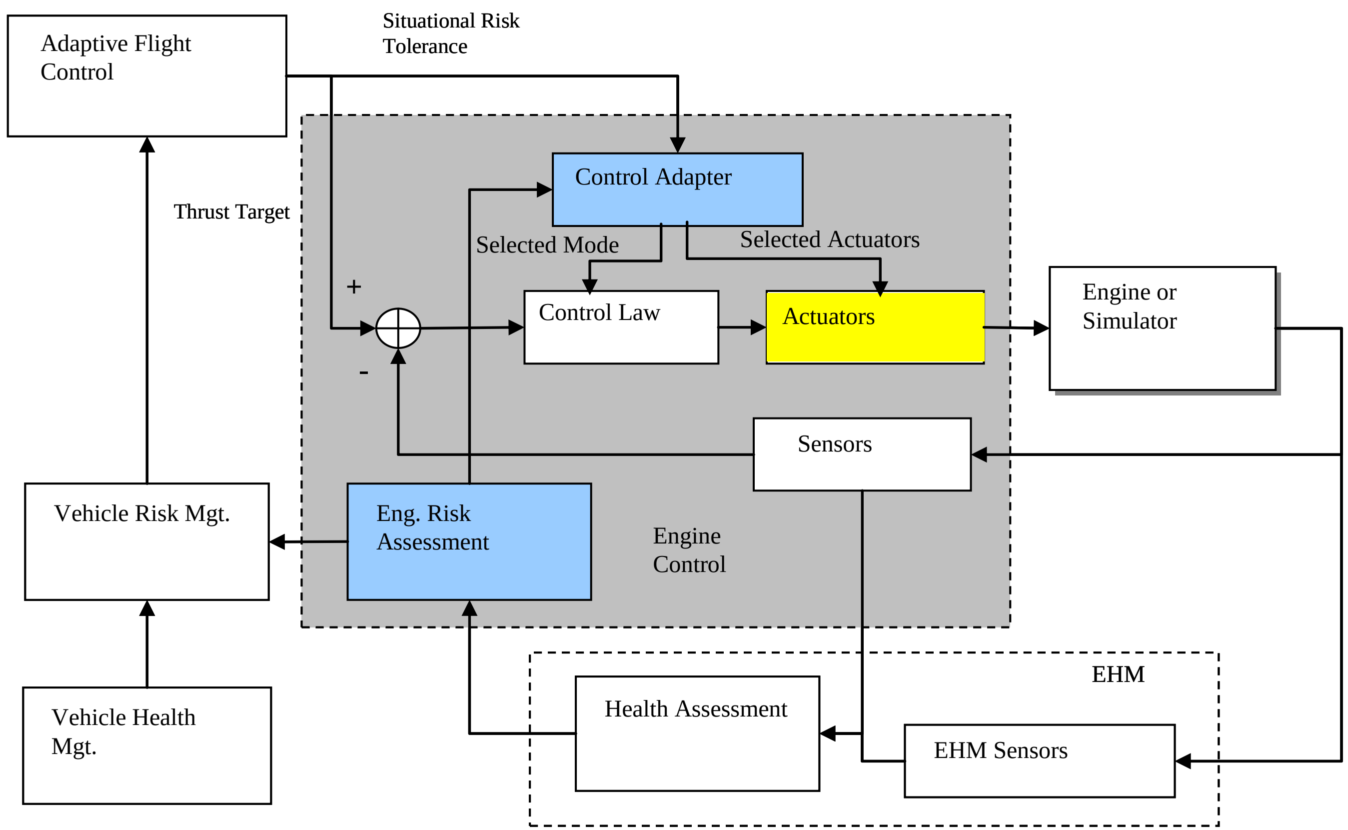
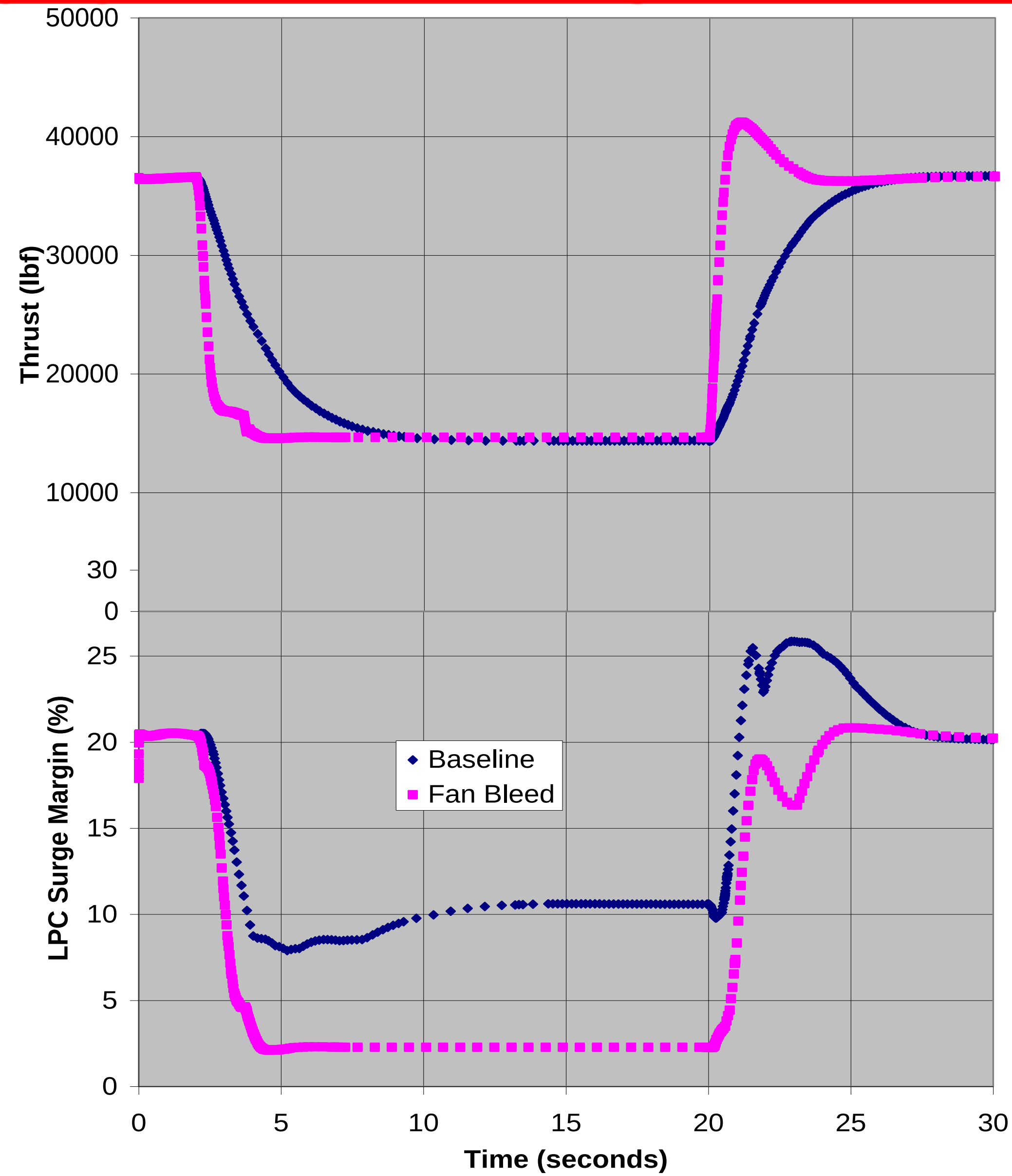


Preliminary Results-Flight Idle



Preliminary Results-Flight Idle

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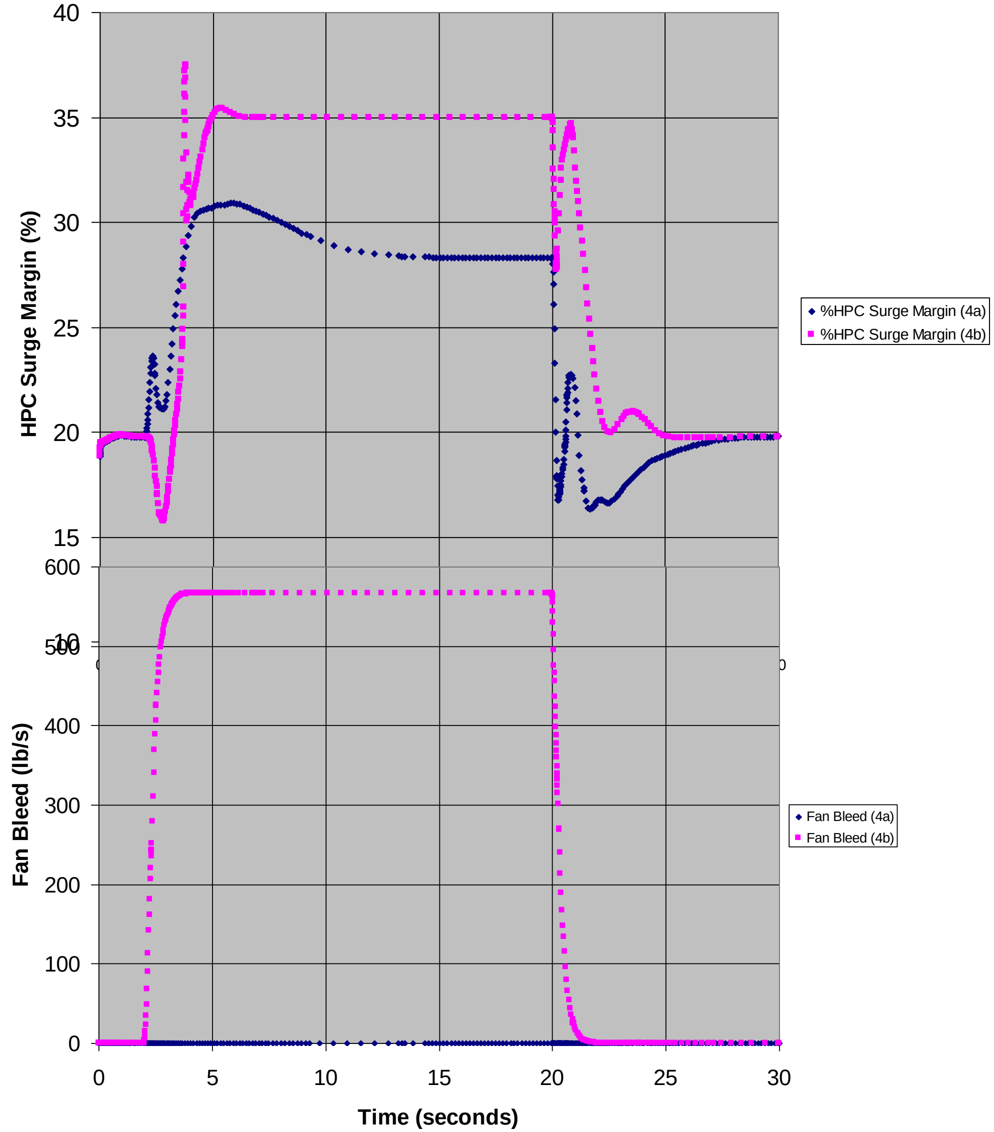

Preliminary Results-Throttle Advance

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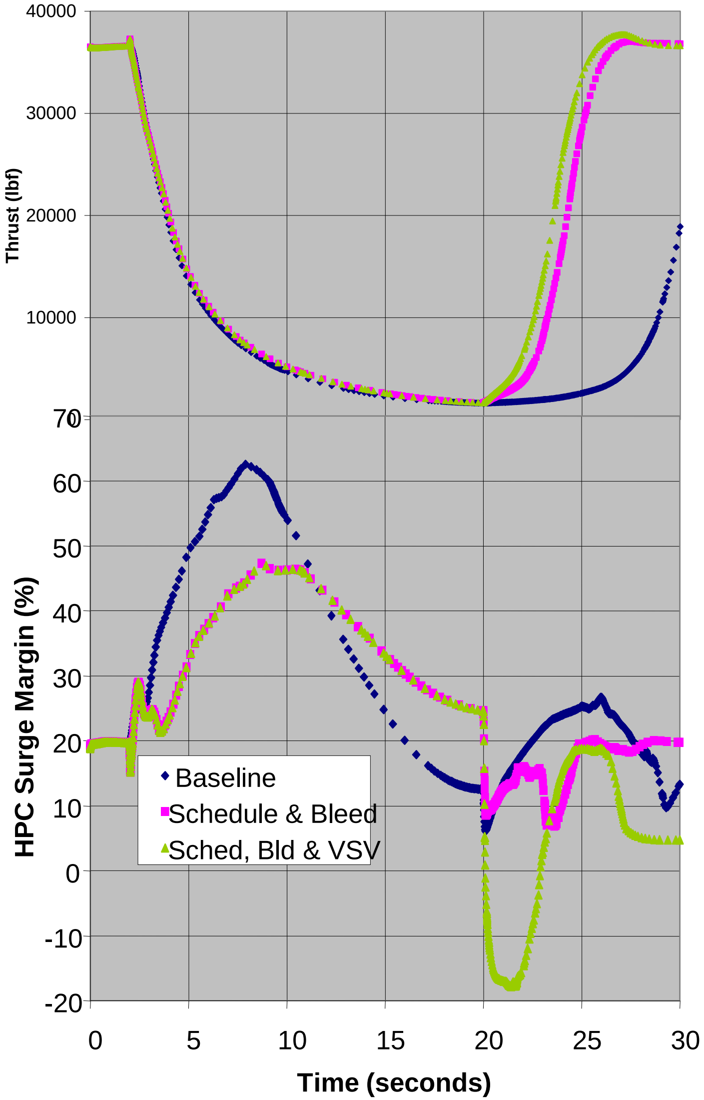
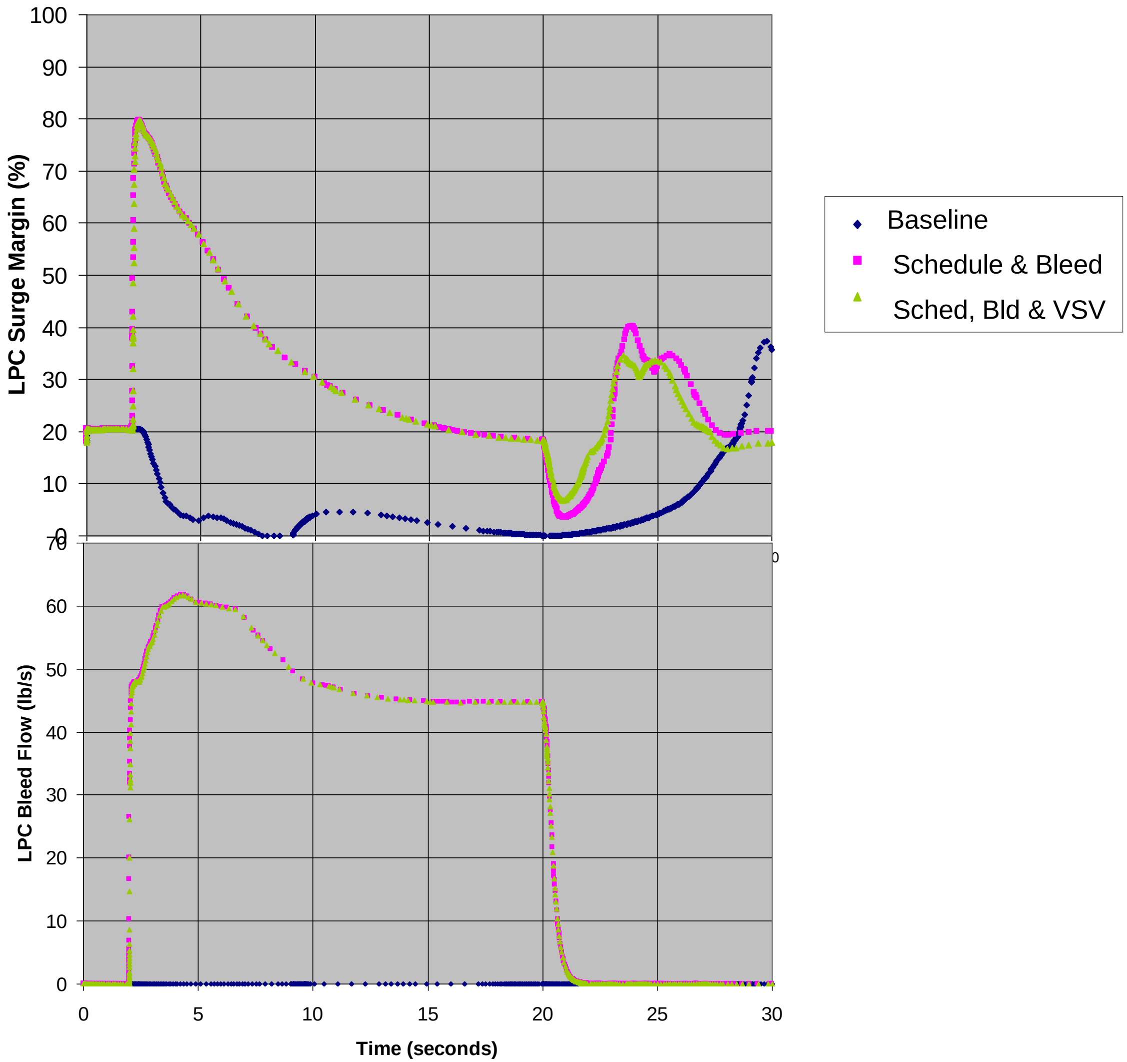


Preliminary Results-Throttle Advance



Yr 2 Technical Approach

- **Define response requirements for engine and aircraft in emergency situations – (Replicated Boeing/PW results using GTM)**
- **Develop fan bleed engine mode – (Incorporated fan bleed and actuation logic in C-MAPSS40k* simulation)**
- **Develop the differential thrust yaw mode – (control incorporates PI mode and thrust splitter logic)**
- **Compare yaw control performance for – (Evaluated performance using GTM/C-MAPSS40k* simulation)**
    - *conventional rudder control*
    - *engine throttle modulation for differential thrust*
    - *fan bleed modulation for differential thrust*
- **Assess engine operation capability & life usage**

General Transport Model - GTM

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The GTM Design Model

- Simulation represents the AirSTAR T-series vehicles
- 5.5%-scale model of a generic twin engine transport
- Aerodynamic database derived from polynomial fit to wind tunnel data. Data include
  - high-angle-of-attack conditions
  - high-sideslip conditions
  - aerodynamic and mass effects on selected damage conditions

Photo Courtesy LaRC

Simulation is in the public domain

- Released under NASA's open-source license
  - which allows the software to be modified and extended by end users
- Simulation development continues
  - Updates to be provided on a regular basis as issues are found and data refined though experimental testing and system calibration.
- GTM-Design simulation availability – contact Melissa.A.Hill@nasa.gov

Yaw Control using Fan Bleed Modulation

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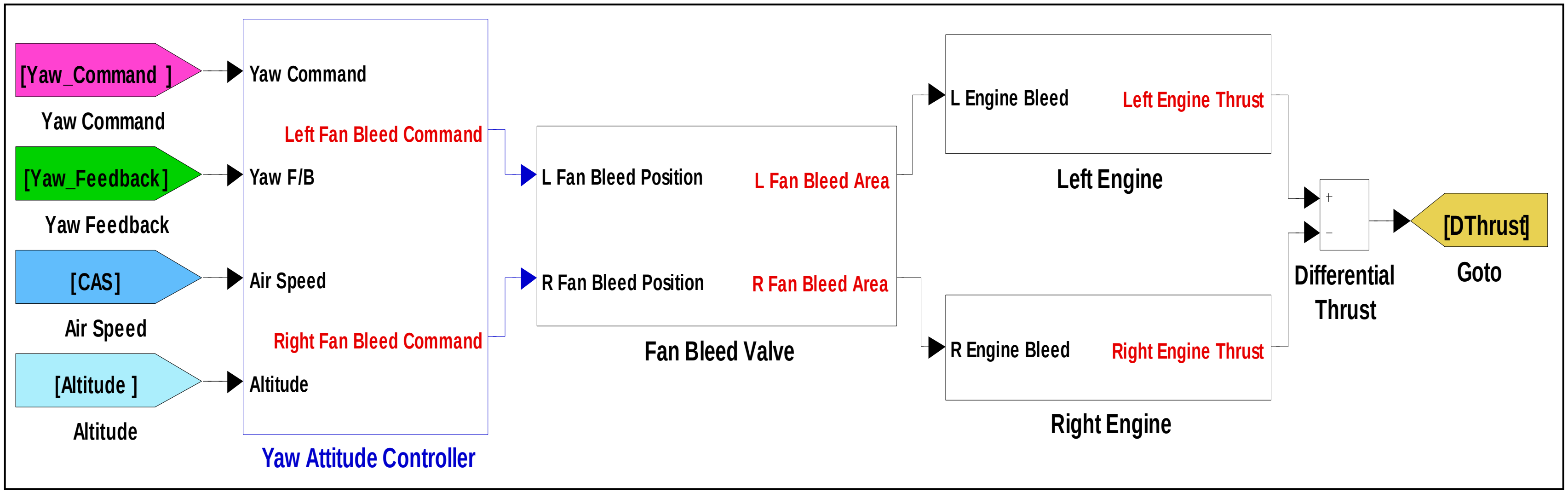
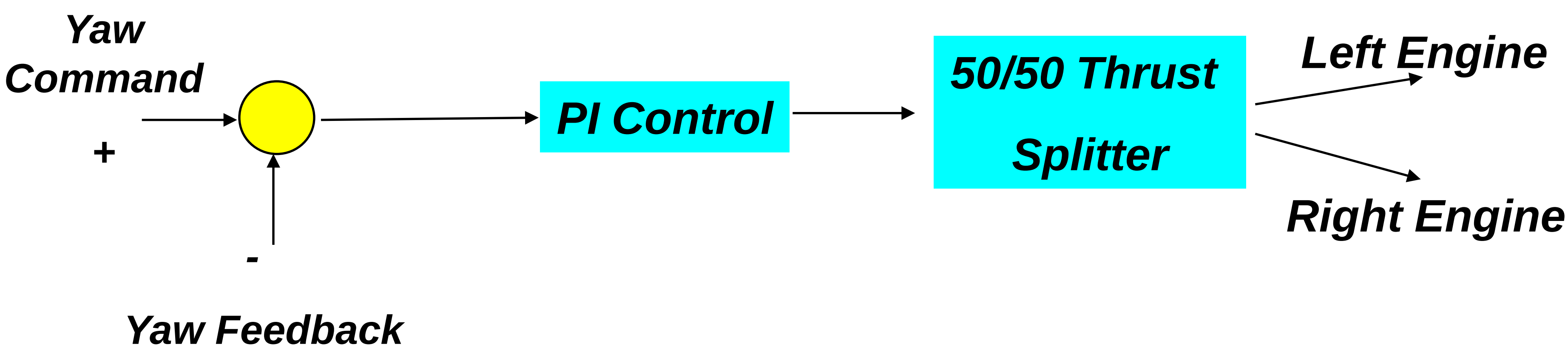
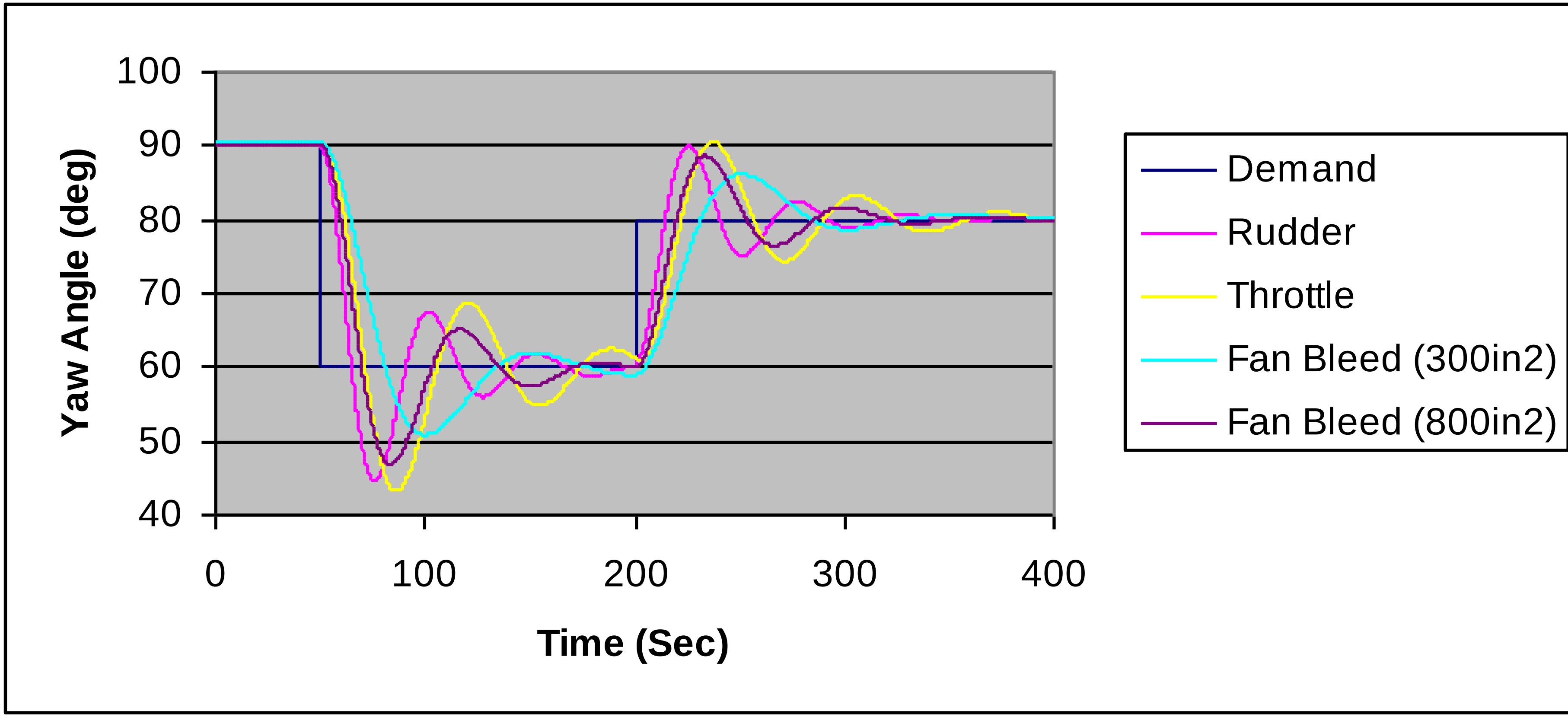




Yaw Control Comparison



Altitude(ft)	Mach	Throttle Range	Nominal Thrust
1110	0.14	50-58	16750

Yaw Control Comparison

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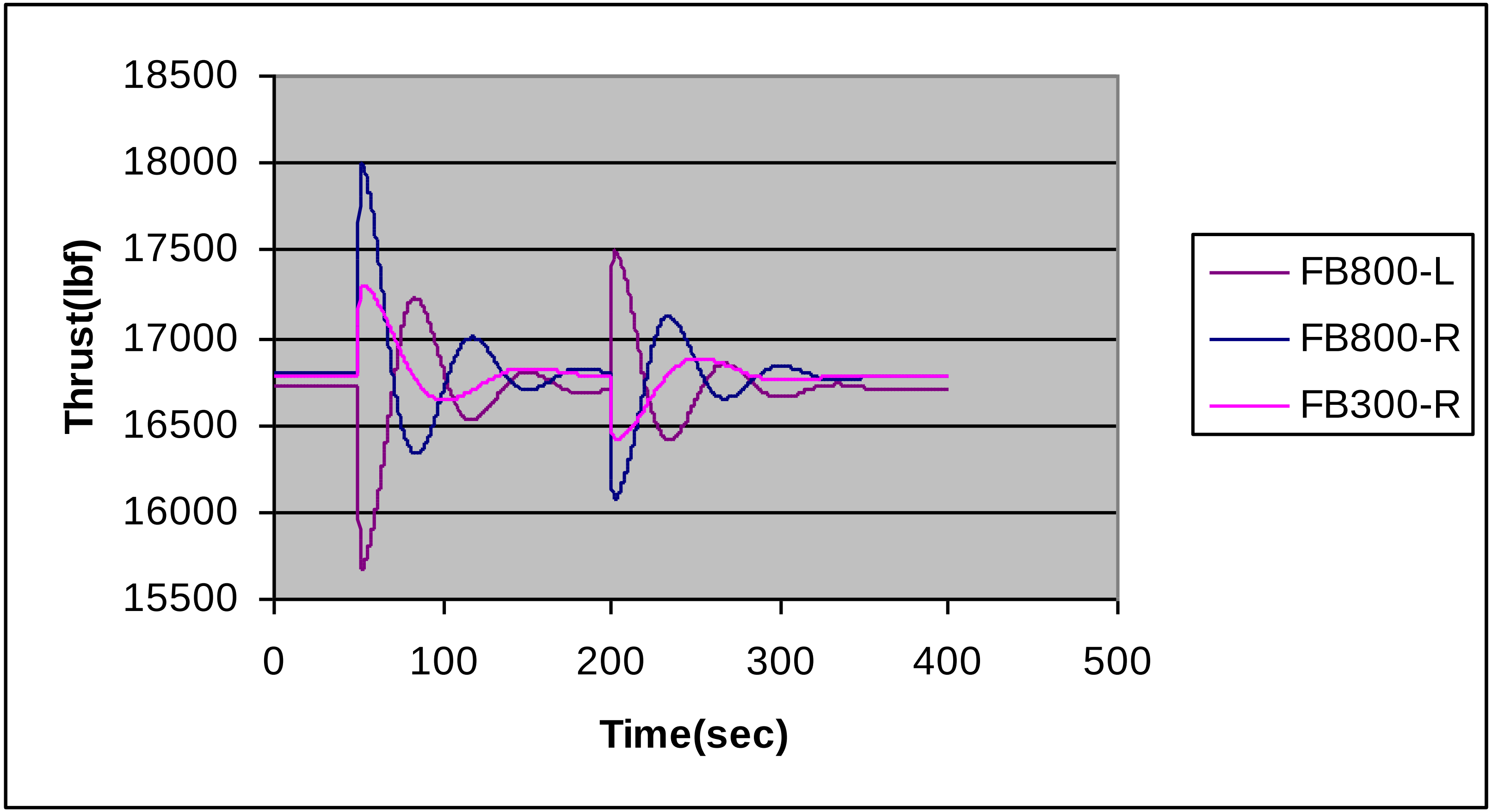
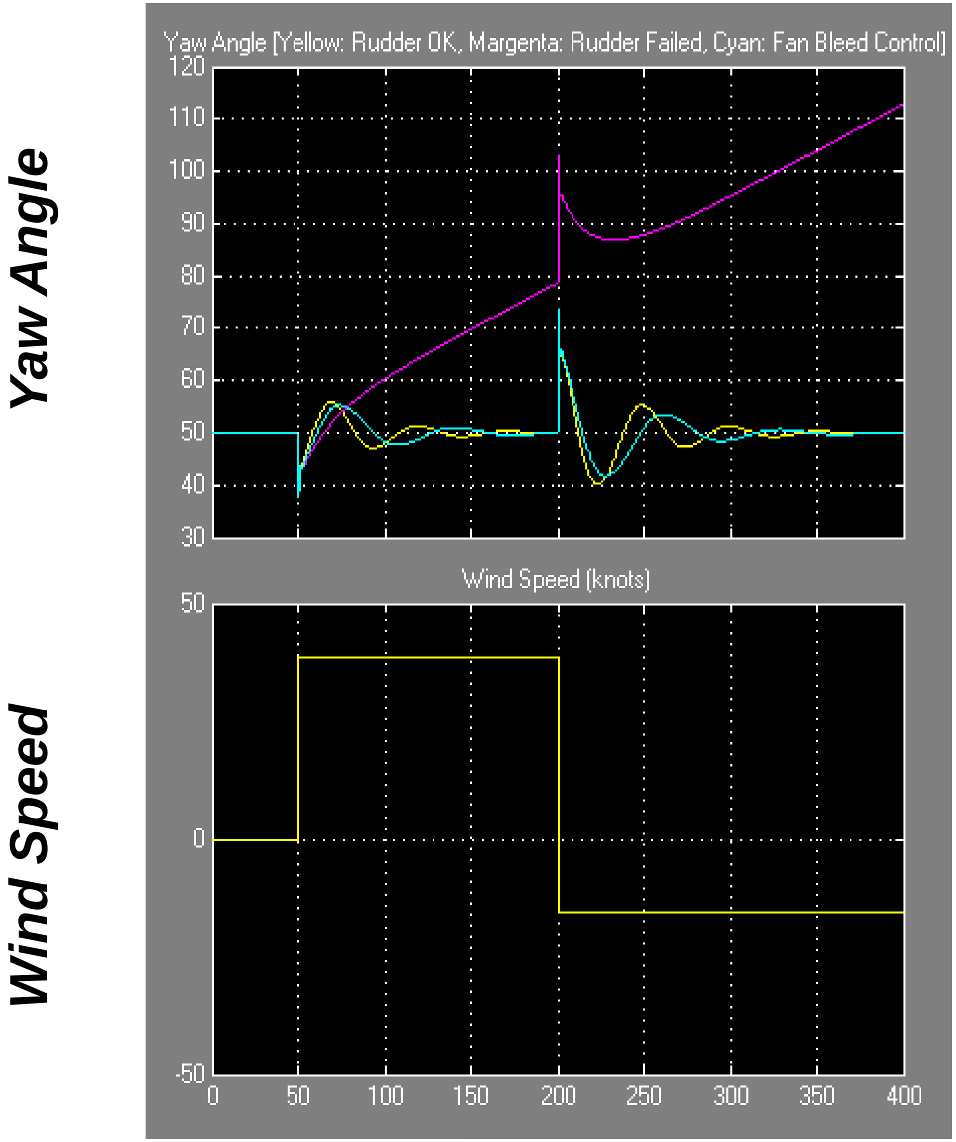


Altitude(ft)	*Mach*	*Throttle Range*	*Nominal Thrust*
1110	0.14	50-58	16750

Yaw Control under Wind Disturbances



Rudder OK – Yellow

Rudder Failed – Magenta

Fan Bleed - Cyan

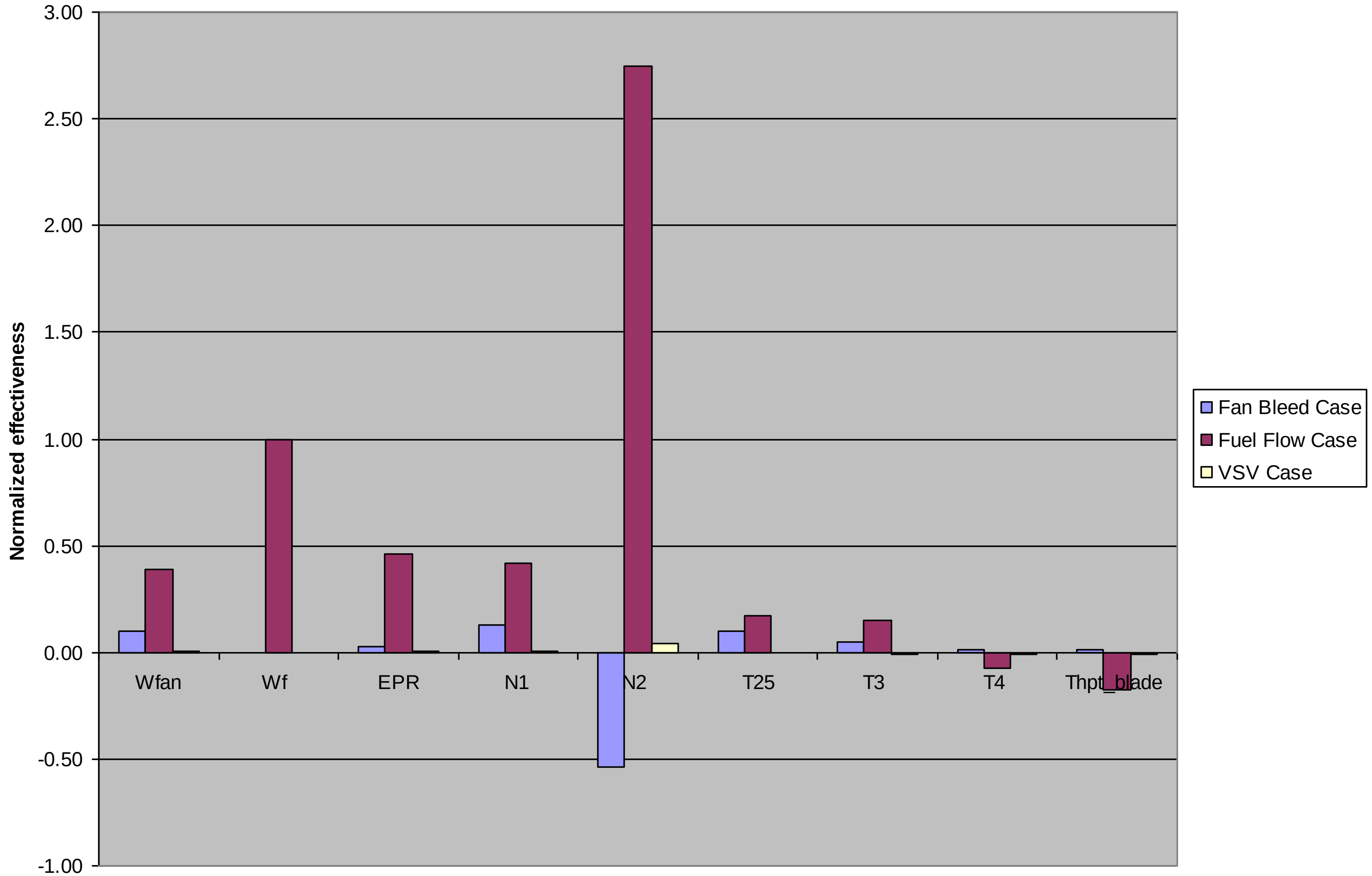
Summary and Conclusions

- **There is a need for Continuous Aircraft Safety Improvements**
  - FastER Engines can substantially contribute to the need
- **Demonstrated to Date**
  - Requirements Definition Scenarios Selected
  - Advanced/New Actuation Proposed
  - Emergency Control Modes Proposed and Selected
  - Initial Control Mode Simulation Results Quite Encouraging
  - Actuator Effectiveness Quantified
  - Yaw attitude control can be achieved through left & right engine differential thrust modulation
  - Differential thrust can be achieved using either fan bleed or throttle lever modulation
  - Yaw attitude control via fan bleed is more effective than via throttle modulation due to faster engine response
  - Stability Margin and Life Usage are not factors due to relatively small thrust changes
- **Next Steps**
  - Integrate Fan Bleed into C-MAPSS40k
  - Integrate C-MAPSS40k into GTM
  - Additional Evaluation of Fan Bleed Control Mode
  - Elaboration of Risk Models
  - Formalize Design Approach

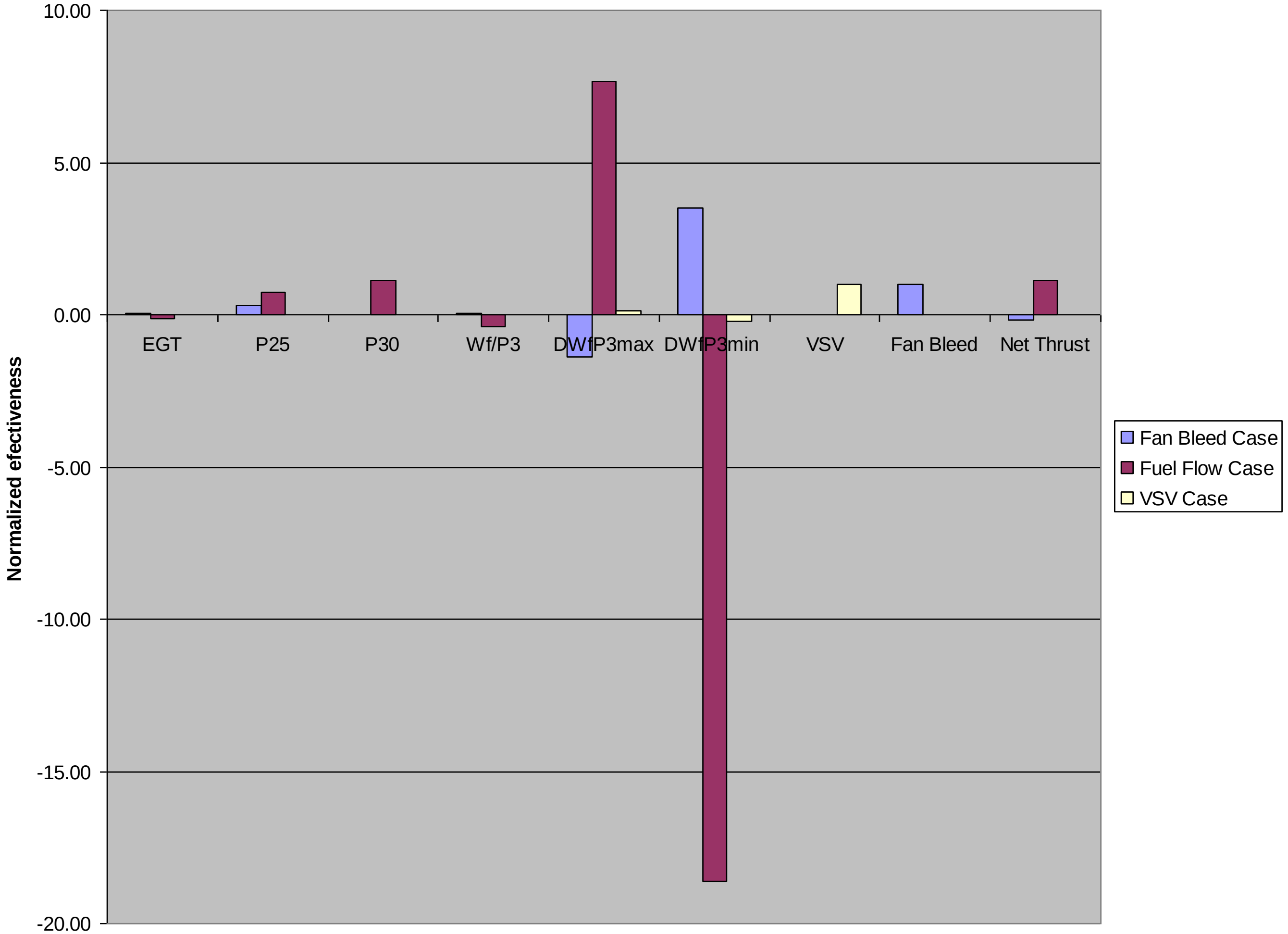
NASA Propulsion Controls Workshop

Backup Material

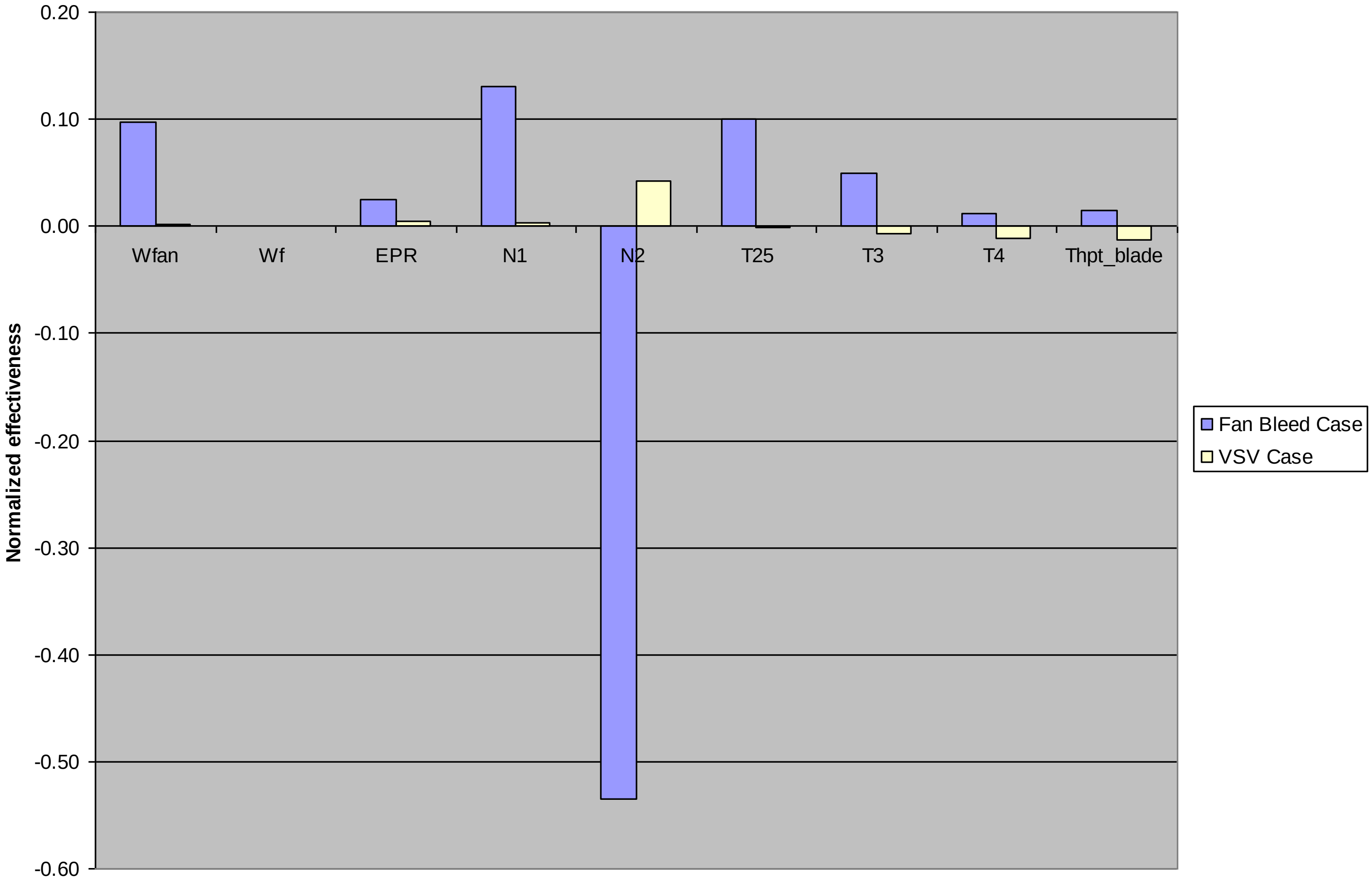
Actuator Effectiveness



Actuator Effectiveness



Actuator Effectiveness-Fbld vs VSV



Actuator Effectiveness-Fbld vs VSV